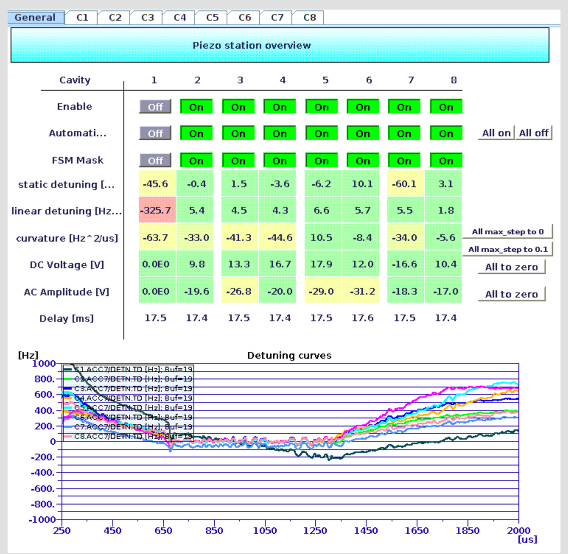
LLRF Automation for the European XFEL

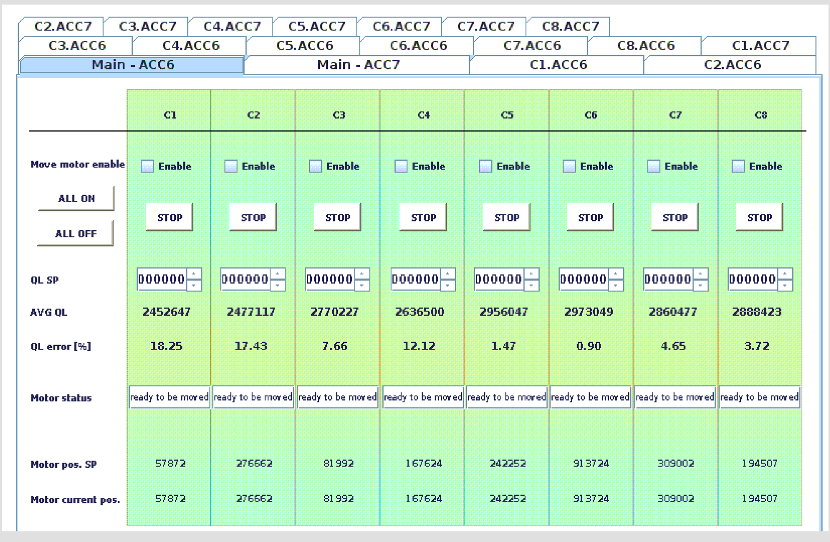
S. Pfeiffer[1], V. Avayzyan[1], J. Branlard[1], W. Cichalewski[2], K. Gnidzinska[2], M. Grecki[1], O. Hensler[1], M. Hoffmann[1], W. Jałmużna[3], A. Piotrowski[2], H. Schlarb[1], C. Schmidt[1],

1 DESY, Germany 2 DMCS-TUL, Poland 3 EicSys GMBH, Poland.

ABSTRACT: The European XFEL will host in total 25 RF stations to accelerate the electron beam to its target energy. A high level of automation is necessary for a reliable and stable machine operation. This contribution details different automation techniques, implemented as part of the LLRF system for cavity resonance and quality factor (Q_L) control, quench detection and prevention, and acceleration energy management.
Implementation and tests have been done at FLASH, where most of these algorithms are now part of routine operation. Recent results and long term integration strategy are presented.

Automation for Machine Operation





> Automatic cavity tuning with piezo.

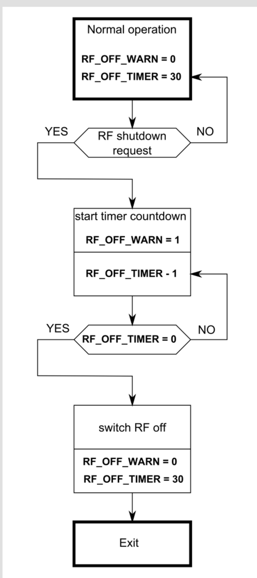
During normal XFEL operation, coarse cavity tuning is performed using the cavity motorized tuner, while fine tuning and compensation for Lorentz force detuning is achieved using piezos. A DOOCS server automates this process by computing the cavity detuning during the pulse, and adjusting the pulsed piezo sinusoidal stimulus parameters (DC offset, AC amplitude, frequency and delay) to maintain a minimal detuning over the duration of the flat top. This server includes protective measures to prevent over-stressing piezos. The frequency and the maximum total amplitude of the excitation are limited. Should the cavity frequency drift outside of the safe piezo tuning range, an alert is given to the operator who can then choose to tune the cavity with the motorized tuner, hence, re-centering the piezo correction in its nominal operating range.

> Automatic Q_L control.

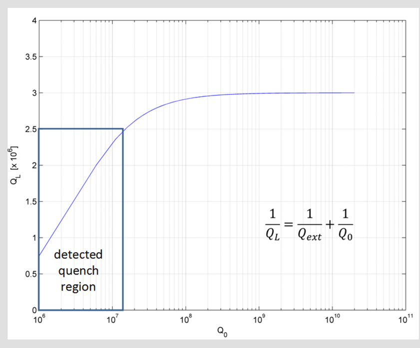
Gradient flattening studies require frequent changes of the cavity loaded Q, so the automation of these settings was necessary. For this purpose, a middle-layer DOOCS server was implemented to perform loaded Q settings. When a new QL setting is requested, the server compares it to the current QL value, which is computed for all cavities and at each RF pulse. The server then moves the coupler motor to modify the position of the coupler antenna, effectively changing the cavity QL and bandwidth, until the measured QL value matches its setting. A simple proportional control scheme is applied, where the input error is the difference between measured QL and setting, and the controller output directly drives the coupler motor. To avoid over exercising the coupler motor, a move is only requested if the QL error exceeds a certain threshold. The server robustness was improved by taking into account exceptions such as out-of-range QL settings, invalid QL measurements or motor reaching the end of its excursion, etc.

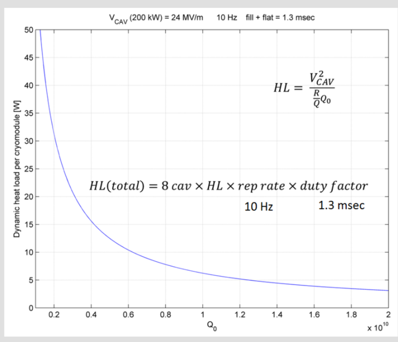
> Automation of Cryogenic – RF operations.

The XFEL cryogenic system is based on cold compressors, which require a very stable Helium return flow. Anytime an RF station is turned off, or on, during normal operation, the cryogenic system must take counter measure to compensate for the fluctuation of dynamic heat load.. This is performed using heaters placed along the cryogenic line. The heaters are turned on when an RF station is turned off, to maintain a constant heat load on the system. This combined actions require reliable communication between RF operations (defined by operators during normal operations) and the cryogenic system.



The impact of repeated cavity quenches, avalanche quenches or soft quenches is still under investigation at DESY and could well be the greatest challenge for RF-cryo operations at the XFEL.

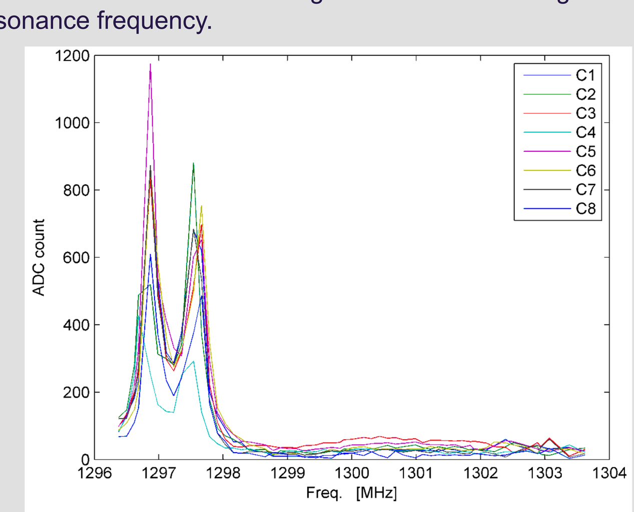




Automation for Machine Commissioning

> Automatic cavity tuning with motors.

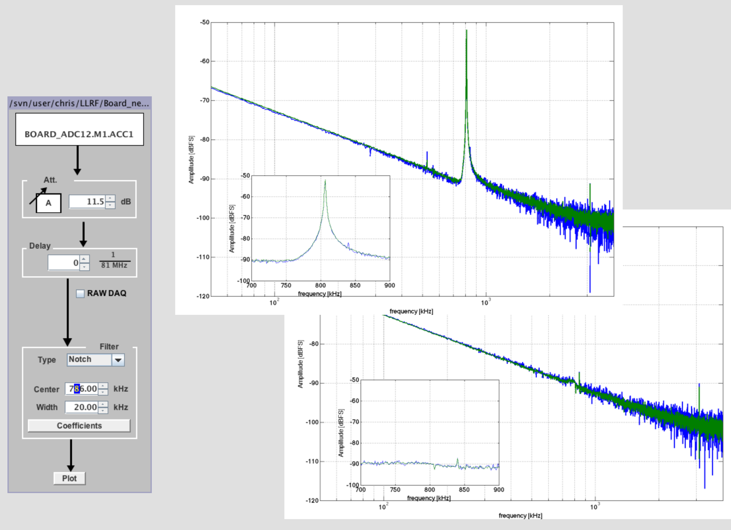
Every time a module is warmed up, the cavity tuners must first be restored to their parking position. Inversely, after cryomodule cool down, all cavities must be tuned to their resonance frequency. An automatic tool is needed to performed both operations. At FLASH, this is performed loading a specific firmware on the LLRF system which performs a phase rotation of the output drive signal, effectively sweeping the frequency of the output signal In parking position, the tuners are at the warm cavity resonance frequency, ~500 kHz away from resonance. This sweeping allows to excite the warm cavities and detect a signal. With the new MTCA.4 LLRF system, the idea is to make use of the ADC higher resolution and higher detection bandwidth to detect a cavity signal without changing the RF frequency. More tests are required to truly assess the feasibility of this method.
Exception handling is of paramount importance. Any motor movement must be checked against the actual change in cavity resonance frequency.

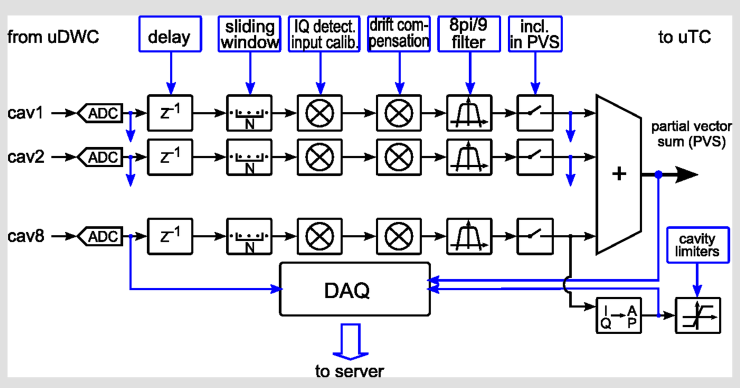


Frequency scan showing the pi and the 8pi/9 mode of the warm cavities.

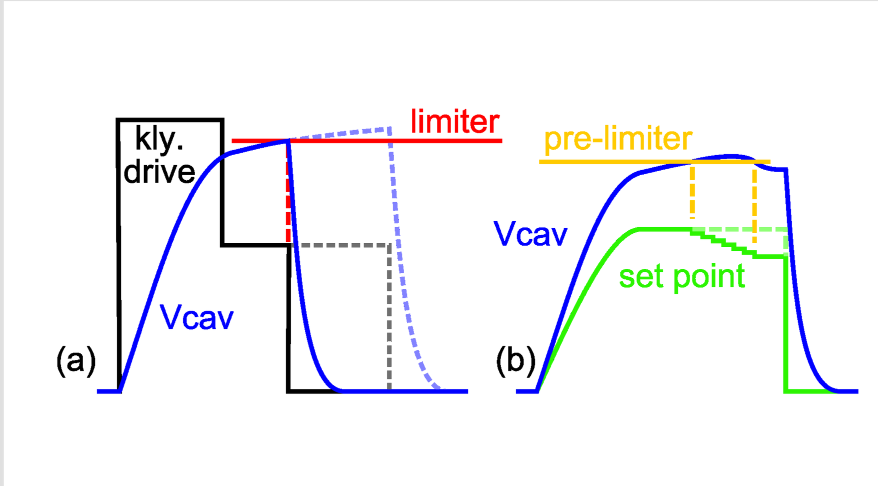
> Automatic notch filter parameter adjustments.

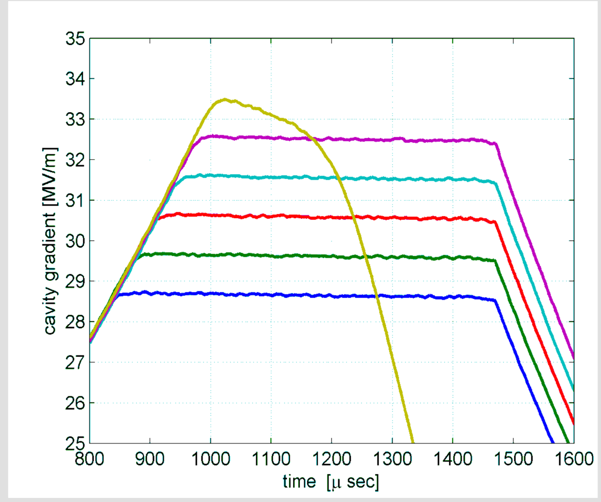
After digitization, all cavity probe signals are going through a digital notch filter, to suppress their 8pi/9 component. During commissioning, the filter parameters (bandwidth, and center frequency) are adjusted for individual cavities. Fine tuning of these parameters can be done while looking at the FFT of the cavity probes.





Automation for Machine Protection





> Cavity gradient limiters (a).

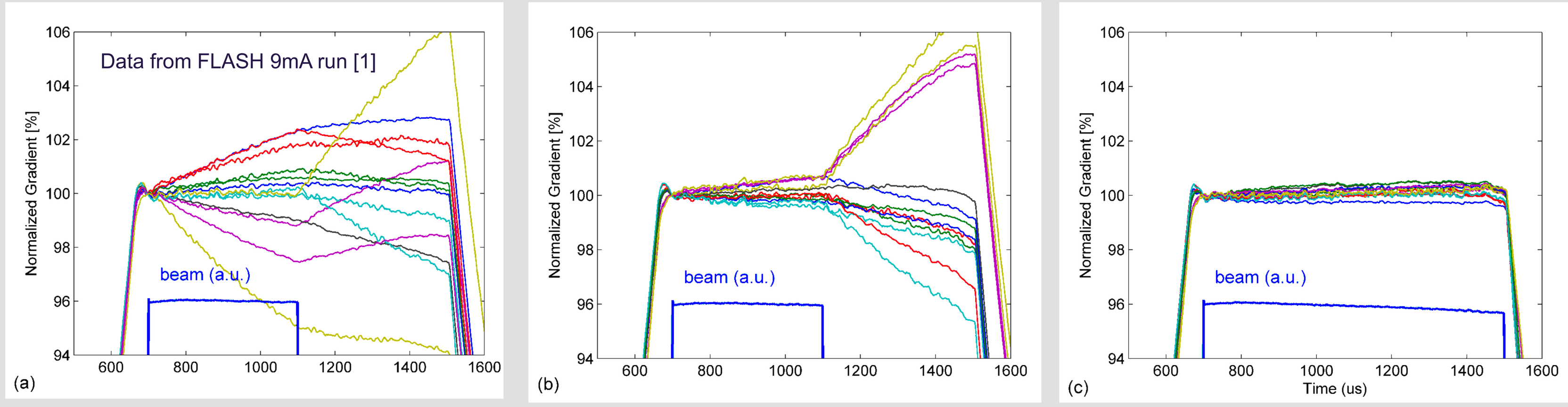
Cavity gradient limiters are implemented inside the controller board, effectively comparing each cavity gradient to a settable threshold for the entire duration of the RF pulse. The RF drive is truncated should one cavity gradient exceed its limiter value. Typically, these thresholds are set to prevent any cavity gradient from going above its quench gradient. As a compromise between safe operation and performance optimization, the limiters are conservatively set 1-2 MV/m below quench limit. This action is effective in feedforward and in feedback mode.

> Cavity gradient pre-limiters (b).

In addition to the cavity limiter described above, each cavity is also assigned a pre-limiter, typically set 0.5-1 MV/m below the cavity limiter. During the RF pulse, every cavity gradient is also compared to its pre-limiter value. If this threshold value is reached (for any cavity), the vector sum set point is lowered within the pulse, by 1 µsec increments until the cavity gradient falls back into its safe zone, or until a maximum number of steps is reached. The action of cavity limiters and the pre-limiters are depicted in Fig. 2. Because it is acting on the vector sum set point, this action is only effective when operating in feedback mode.

> Quench detection [2].

A quench detection server compares individual cavity QL to their previous values averaged over the last N pulses (N 20). A sudden drop in QL (typically larger than 5 × 105) triggers a quench alert which results in shutting the RF off on the next pulse. Due to server latency and server to server communication overhead, the reaction to a detected quench can be delayed by one pulse (XFEL will operate at a 10 Hz repetition rate), resulting in two quenched pulses. This does not constitute a problem for the cryogenic plant which has enough overhead to handle several quenches.



> Step 1: default Q_L , short beam train.

Initially, all cavities have their Q_L set to the default 3×10^6 value. The beam train is kept short (400 µsec) and the gradient tilts induced by the beam loading are clearly visible during the first 400 µsec of the flat top

> Step 2: optimize Q_L for beam current.

The individual cavity Q_L are then optimized automatically so that all gradients are flat with beam. While the optimized Q_L values flatten the gradients with beam, they also worsen the tilts in the flat top region where no beam is present.

> Step 3: extend beam train with optimized Q_L.

In the last step (c), the beam train is extended to its full 800 µsec. With optimized Q_L, all gradients were kept flat with a 0.2% peak-to-peak accuracy.

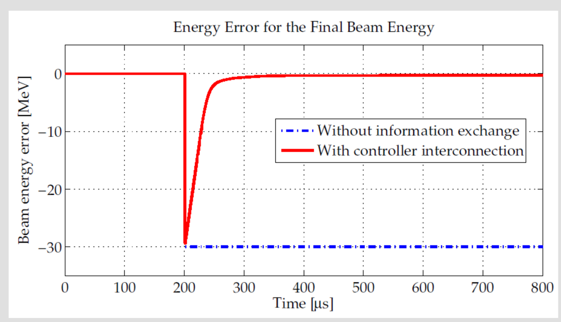
[1] LLRF Automation for the 9mA ILC tests at FLASH.
J. Branlard, V. Ayvazyan, O. Hensler, C. Schmidt, N.J. Walker, M. Walla, H. Schlarb, DESY, Germany
G. Cancelo, B. Chase, FNAL , USA
J. Carwardine, ANL, USA
W. Cichalewski, W. Jałmużna, DMCS-TUL, Poland
S. Michizono, KEK, Japan.
LINAC 2012, Tel Aviv, Israel

[2] Superconducting Cavity Quench Detection and Prevention for the European XFEL
J. Branlard, V. Ayvazyan, O. Hensler, C. Schmidt, H. Schlarb, DESY, Hamburg, Germany,
W. Cichalewski, DMCS, Ł´od´z, Poland,
ICALEPCS 2013, San Francisico, USA

Automation for Machine Optimization

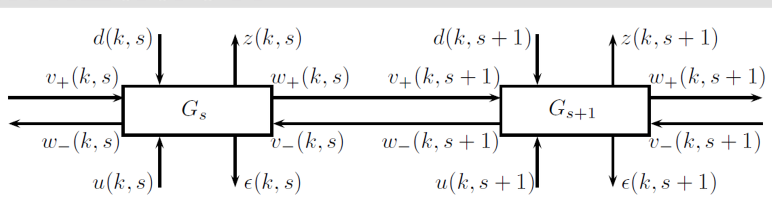
> Slow and fast energy management [3]

The energy optimization among different RF stations is handled by high-level DOOCS servers. This optimization needs interfacing with the cryogenic system, with magnets and with optics controls. The amount of allowed RF gradient change for such an energy management should be clearly agreed among the different subsystems. The slow global energy management server takes action gradually, from RF pulse to RF pulse. The fast global energy management server can take action within the same RF macro pulse.

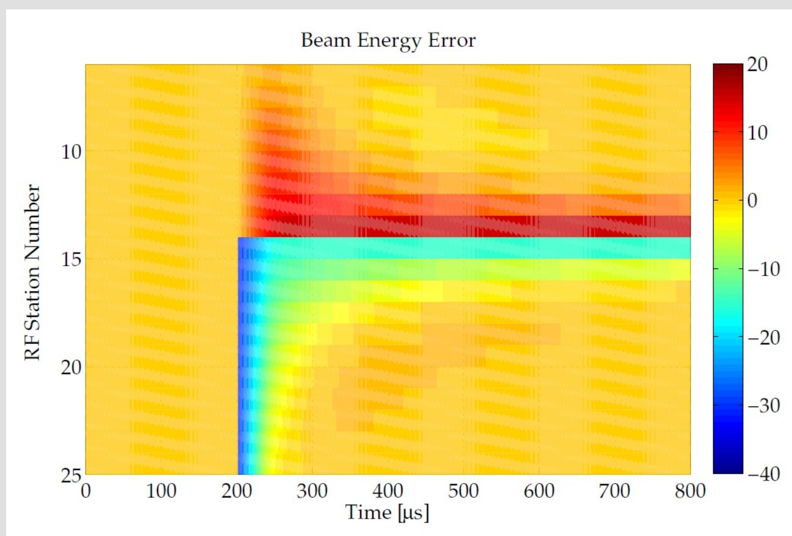


[3] Distributed Controller Design for a Free-Electron Laser
S. Pfeiffer, C. Schmidt, H. Schlarb, DESY, Hamburg, Germany,
H. Werner, ICS, Hamburg University, Germany
American Control Conference (ACC 2013) , Washington, USA

Both servers detect any exception at a given RF station which results in a decrease of the operational gradient. The gradient loss is then distributed between the neighbouring stations, upstream and down-stream, within acceptable tolerances. The goal of these servers is to optimize the energy distribution among RF stations, while attempting to minimize machine down-time. This energy management serves on two levels, as exception handling to continue safe operation when an exception occurs but also as a safeguard against unacceptable machine operation changes triggered by operators.



Spatially interconnected system, where subsystem G_s is given with a fictive input $d(k,s)$ and fictive output $z(k,s)$, the plant input $u(k,s)$ and plant output $\epsilon(k,s)$ and the interconnections input $v(k,s)$ and $w(k,s)$ as output, respectively.



CONCLUSION:

> Many automation tools have already been implemented at FLASH, based on years of operation and commissioning of a super conducting linac (MATLAB → DOOCS).

> With the installation of the XFEL LLRF system at FLASH, the potential for automation has increased. More tools are being developed and tested at FLASH in preparation of a large scale implementation at the XFEL.

> As for all automation tools, exception handling is key to robust and reliable algorithms .

> Already observed in previous tests, competition between automation tools can also yield precarious situations. A robust finite state machine acting as arbiter is also necessary on a large scale machine.

> The major part of hardware work is now finished for the XFEL, the bulk of the remaining tasks are software and tool development